Indirect dark matter searches: Towards a consistent top-bottom approach for studying the gamma-ray signals and associated backgrounds

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Abstract: While dark matter (DM) is the key ingredient for a successful theory of structure formation, its microscopic nature remains elusive. Indirect detection may provide a powerful test for some strongly motivated DM particle models. Nevertheless, astrophysical backgrounds are usually expected with amplitudes and spectral features similar to the chased signals. On galactic scales, these backgrounds arise from interactions of cosmic rays (CRs) with the interstellar gas, both being difficult to infer and model in detail from observations. Moreover, the associated predictions unavoidably come with theoretical errors, which are known to be significant. We show that a trustworthy guide for such challenging searches can be obtained by exploiting the full information contained in cosmological simulations of galaxies, which now include baryonic gas dynamics and star formation. We further insert CR production and transport from the identified supernova events and fully calculate the CR distribution in a simulated galaxy. We focus on diffuse gamma rays, and self-consistently calculate both the astrophysical galactic emission and the DM signal. We notably show that adiabatic contraction does not necessarily induce large signal-to-noise ratios in galactic centers, and could anyway be traced from the astrophysical background itself. We finally discuss how all this may be used as a generic diagnostic tool for galaxy formation.

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Indirect dark matter searches: Towards a consistent top-bottom approach for studying the gamma-ray signals and associated backgrounds

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While dark matter is the key ingredient for a successful theory of structure formation, its microscopic nature remains elusive. Indirect detection may provide a powerful test for some strongly motivated DM particle models. Nevertheless, astrophysical backgrounds are usually expected with amplitudes and spectral features similar to the chased signals. On galactic scales, these backgrounds arise from interactions of cosmic rays (CRs) with the interstellar gas, both being difficult to infer and model in detail from observations. Moreover, the associated predictions unavoidably come with theoretical errors, which are known to be significant. We show that a trustworthy guide for such challenging searches can be obtained by exploiting the full information contained in cosmological simulations of galaxies, which now include baryonic gas dynamics and star formation. We further insert CR production and transport from the identified supernova events and fully calculate the CR distribution in a simulated galaxy. We focus on diffuse gamma rays, and self-consistently calculate both the astrophysical galactic emission and the dark matter signal. We notably show that adiabatic contraction does not necessarily induce large signal-to-noise ratios in galactic centers, and could anyway be traced from the astrophysical background itself. We finally discuss how all this may be used as a generic diagnostic tool for galaxy formation.

An important issue arising in indirect dark matter (DM) searches is our limited capability for predicting the astrophysical backgrounds accurately enough (for reviews, see [1]). In the last decade, several claims for smoking guns have shown up in the literature, usually followed (sometimes preceded) by conventional astrophysical explanations (*i.e.* other astrophysical sources or wrong background models). For examples at the Galactic scale, one may find the *WMAP haze* [2], which might be due to an improper background extrapolation [3], or at the cosmic positron excess [4], which triggered a plethora of DM proposals (*e.g.* [4]), while pulsars have long been known to be good candidates (*e.g.* [5]).

Gamma rays are probably the best messengers for seeking DM annihilation traces because of the favorable experimental landscape and because they propagate freely from their source to the observer, thereby reducing the theoretical uncertainties in predictions with respect to charged species. The best targets are those which can be localized accurately and are not background polluted: nearby dwarf galaxies. Nevertheless, current experimental sensitivities fall just too short [6, 7]. Another possibility is to examine the diffuse gamma-ray emission (DGRE), for instance its angular and/or spectral gradients (*e.g.* [8, 9]). However, it is often difficult to interpret the data because of uncertainties in Galactic background models (see [**?**] in light of [11]). One way around this is to focus on spectral features specific to DM models, like gamma-ray lines or spectral hardenings due *e.g.* to the prominence of bremsstrhalung annihilation diagrams [4, 12**?**]. Unfortunately, current experiments do not yet have the required energy resolution to achieve a good enough background rejection, and no such features have been discovered so far. Therefore, a much deeper understanding of the astrophysical backgrounds seems now necessary to go from speculation to stronger evidence. We focus on gamma rays in the following.

The main astrophysical background comes from interactions of CR nuclei (mostly protons) with the interstellar gas. It also originates in inverse Compton scattering of CR electrons off the interstellar radiation fields and the cosmic microwave background, but we disregard this subdominant component here ($\lesssim 10\%$ of the DGRE measured by Fermi at 1 GeV [**?**]). Hence, a complete prediction of the DGRE depends on both the Galactic gas and

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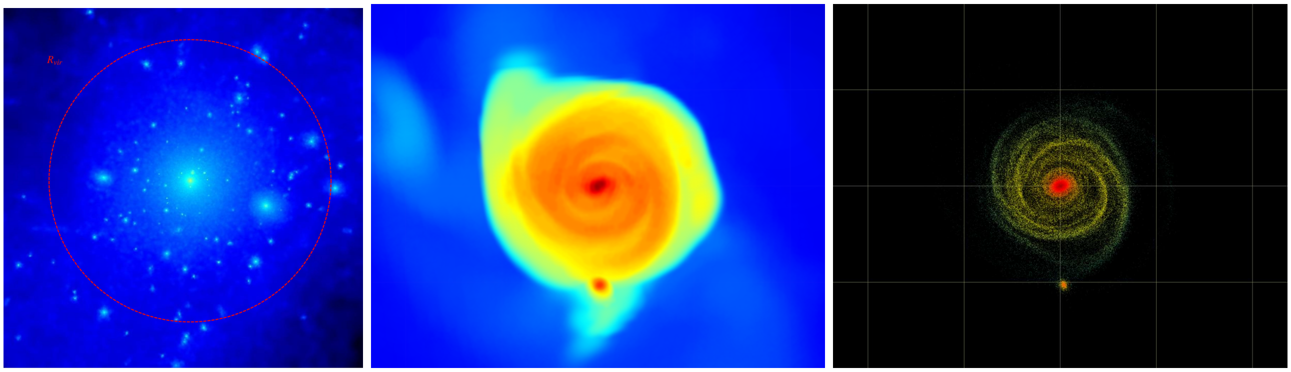

FIG. 1. Left: DM halo and subhalos; the virial radius (264 kpc) appears as a red circle. Middle: top view of the gas content (scaled as in right panel). Right: SN events in the last 500 Myr (10 kpc grid).

CR distributions. For the former, models are based on line-of-sight observations (21 cm for instance) that must be deconvolved in agreement with the global Galactic dynamics, a difficult reconstruction procedure subject to ambiguities (*e.g.* [14]). For the latter, one should in principle know about the real distribution of the CR sources in space and time, the precise mechanism of acceleration and escape, and the physics of CR transport in the interstellar medium. While the latest points still call for theoretical developments, the first one, one of the most critical, remains difficult to infer from observations.

A solution to get more insights about these issues is to *build* a template galaxy from first principles, wherein all ingredients relevant for testing indirect detection are found with the correct physical correlations. This has actually become possible since the advent of cosmological simulations of galaxies including baryons and star formation (so-called *zoom-in* cosmological simulations[1]). Indeed, the resulting virtual objects are cosmologically and dynamically self-consistent, and while star formation is still treated semiempirically, they offer a perfect environment to assess the discovery potential of indirect DM detection. Beside fully characterizing the DM and baryonic gas contents, one can also trace the star formation history and localize the supernova (SN) events in space and time. From these SNRs, a still missing step is to plug in the injection of high-energy CRs and their transport further away in the galaxy. A fraction of the SNe energy is actually already used in the form of feedback, a mechanism which regulates the adiabatic contraction of DM [15] due to the cooling of baryons—the same mechanism is also responsible for CR acceleration. Once the CR distribution is known, the astrophysical DGRE can be calculated and compared to the DM annihilation signal which scales like the squared DM density.

[1] The *zoom-in* technique consists of identifying a candidate galactic halo in a low resolution DM-only simulation, and then resimulating it with baryons and with a much better resolution at the candidate halo position.

We use a zoom-in simulation performed with the cosmological adaptive mesh refinement code RAMSES [16], which includes the baryon gas dynamics and star formation. Technical details will be found in [17]. At redshift $z = 0$, the selected galaxy has a virial radius $R_{200} = 264$ kpc and features a baryon disk of ~ 10 kpc radius. The dark halo mass is $M_h \sim 6 \times 10^{11} M_\odot$, while the bulge and disk masses are both $\sim 4 \times 10^{10} M_\odot$, which implies a gas concentration larger than in the Galaxy. This induces a contraction of the DM density profile in the center, where the logarithmic radial slope is found around -1.5, though saturating in the inner 200 pc due to resolution limits — a consequence of adiabatic contraction. We resolve 79 subhalos, carrying 4.8% of the total mass. The closest object to the galactic center lies at a distance of 12.7 kpc. The different components of our simulated galaxy are shown in Fig. 1.

Our setup suffers some limitations that we shortly discuss here. They mostly come from our limited spatial resolution of ~ 200 pc. First, the vertical extent of the disk is not very well-resolved. Moreover, we cannot study in detail the effects of DM subhalos, but it is anyway still hard to incorporate the full baryon treatment in simulations as resolved as in *e.g.* [18]. Nevertheless, small subhalos are not expected to accrete ordinary matter efficiently so results based on semianalytic studies remain valid (*e.g.* [9] for gamma rays and [19] for antimatter CRs). Finally, we note that subsequent improvements in the feedback treatment have recently allowed for better control of the overcooling of baryons at halo centers (*e.g.* [20]), which could have led to a flatter and more extended disk, a less prominent bulge, and a less spiky DM profile. Nevertheless, our numerical treatment can still be considered robust given the uncertainties affecting the implementation of star formation and feedback in cosmological simulations [**?**]. Besides, these limitations do not qualitatively affect the present study which proposes a global phenomenological strategy. Our method, that we detail below, can easily be applied to more sophisticated cosmological simulations.

We identified all SN events in the latest 500 Myr of

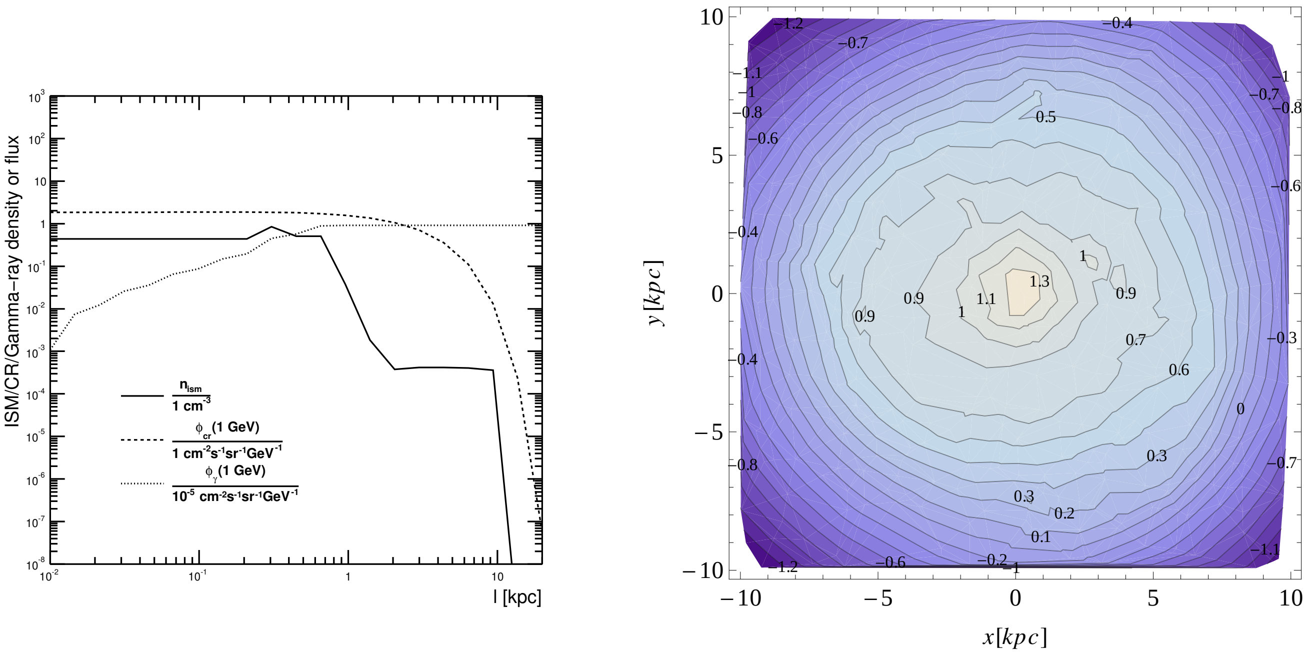

FIG. 2. Left (units in the legend): Vertical gradients of the ISM gas (solid curve) and of the CR flux (dashed curve). The resulting cumulative gamma-ray flux for an observer located at coordinates $(x, y, z) = (0, 8, 0)$ kpc is shown as the dotted curve. Right: CR flux gradient in the galactic plane (in $\log_{10}\{\Phi_{\rm cr}(>1{\rm GeV})/{\rm cm}^{-2}{\rm s}^{-1}{\rm sr}^{-1}\}$).

the simulation, for which we recorded the space-time coordinates. This timescale is taken slightly larger than the residence time of CRs in the galaxy, which is set by the diffusion coefficient and the size of the reservoir. SNe are defined from the fraction of massive stars (with masses fixed to $10\,M_\odot$ here), which amounts to $\sim 10\%$ of all stars. These massive stars are given a fixed lifetime of 20 Myr, after which they end as SNe, each converting its core mass into pure energy. For each SN, about 10^{51} erg is transferred to the surrounding material in the form of kinetic energy, 10% of which is used as feedback energy. As a supplementary step, we also convert about 10% of this kinetic energy into high-energy CRs with power-law energy spectra. To our knowledge, this stage is still unprecedented on galactic scales (see [22] for a complementary approach). We recorded about 85,000 SN-like events (*i.e.* ∼85,000 star *particles* have formed). In terms of real SNe (end products of $10\,M_\odot$ stars), this translates to $\sim 1.5 \times 10^7$ events, corresponding to an explosion rate of ∼3/100 yr.

To get the full CR distribution through the galaxy, we plug in a full semianalytic computation of CR transport by means of Green's functions, using the space-time information associated with the sources (SNe). We only consider CR protons and Helium ions, *i.e.* the most relevant species to calculate the hadronic part of the DGRE, with kinetic energies above a few GeV. Such an energy threshold allows one to neglect convection and spallation processes when ascribing the (time-dependent) transport equation that CRs do obey (for details on CR propagation, see *e.g.* [23]). In this regime, CRs are mostly subject to spatial diffusion. Diffusion should depend on the galactic magnetic field properties, but we lack this piece of information in our simulation. While seeding the magnetic field is still an open issue, we may still envisage to incorporate it semi-consistently in future studies by evolving arbitrary primordial seeds such that its typical amplitude on galactic scales at redshift 0 is a posteriori consistent with current observations [24]. Instead, we assume a rigidity-dependent, isotropic and homogeneous diffusion coefficient, such as in most of models of Galactic CRs [25]: $K(\mathcal{R} \equiv |p|/q) = 0.01\,{\rm kpc}^2/{\rm Myr}\,(\mathcal{R}/1\,{\rm GV})^{0.7}$. This leads to a maximal range of ~ 5 kpc for CRs originating from the oldest sources. The injected CR spectrum at SN sources (before transport) is taken to be universal, scaling like E^{-2}. The DGRE is calculated by convolving the CR flux with the interstellar gas density, for which we adopt a fixed relative amount of hydrogen:helium of 9:1. A top view of the gas distribution is shown in the middle panel of Fig. 1. For the hadronic cross sections, we used the semianalytic formulæ proposed in [26], with the nuclear weights of [27].

We illustrate our results by assuming a virtual observer located in the disk at position $(0, 8, 0)$ kpc, in Cartesian coordinates (the disk belongs to the x-y plane), as a reference to a hypothetical observer on Earth. Yet, this is hard to compare with real Galactic data since our simulated galaxy does not provide a realistic picture of the Milky Way (MW). Nevertheless, we can delve into useful qualitative discussions and sketch a roadmap for future and more detailed analyses. In the left panel of Fig. 2, we plot the vertical gradients of (i) the CR flux measured at 1 GeV, and (ii) the ISM gas density; we also plot the local cumulative photon flux at 1 GeV (the hadronic component), proportional to the line of sight integral of the product of the two previous quantities. For the hypothetical observer, this would correspond to a set of data associated with Galactic coordinates ($l = 0°, b = 90°$). We see that the gaseous disk extends up to 1 kpc, larger than our Galactic disk at the Sun's position, whose half-width is ~ 100 pc [28]. The CR density has a slightly broader and smooth vertical distribution, and experiences an exponential cutoff above a few kpc, which is rather consistent with the size of the diffusion zone used in the MW. This is not due to any vertical boundary condition, but to the maximal range CRs can reach within 500 Myr (sources are confined in the disk). Finally, the hadronic part of the local DGRE is obviously found to saturate when the gas density shrinks. Our results are actually shown as dimensionless ratios, where the denominators have been taken with values close to what is measured on Earth. Note that these ratios are $\mathcal{O}(1)$. We show the overall CR flux gradient as projected in the disk in the right panel of Fig. 2. No cylindrical symmetry appears, as is usually assumed in most CR models.

As a final series of illustrations, we have explicitly calculated the gamma-ray skymap that our virtual observer would measure (flux integrated above 1 GeV, smeared over an angular window of 0.01 squared degree). In the left panel of Fig. 3, we show the contribution of DM annihilation, where we assumed a 100 GeV WIMP annihilating into $b\bar{b}$ quark pairs with a canonical thermal cross section of $\langle \sigma v \rangle = 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$. This map exhibits an almost spherical symmetry around the galactic center, a well-known property of DM halos. The signal concentrates in the very center, while four other hot spots are also visible. These are subhalos with masses M in the range 10^8-10^9 $M_\odot$, and lying at distances d between 20-30 kpc from the observer. This mass range is that of the most massive dwarf galaxy satellites of the MW. Since the subhalo gamma-ray flux scales like $\sim M/d^2$, we note that the spots obtained here are much brighter, by 2 or 3 orders of magnitude, than what we would expect from the MW satellites, which are more distant. In the middle panel, our calculated astrophysical background is shown with the same level of precision, for which we see a much flatter and smoother distribution than for the DM-induced component. We make the ratio in the right panel: regions favorable to DM searches are around the galactic center and a few massive subhalos, as expected.

Of course, the virtual observer would only measure the sum of the left and middle panels, and would have difficulties in reaching such conclusions without an accurate and reliable background model, while the background map is exact in our case. Nevertheless, this already really allows one to assess the potential of indirect DM detection with gamma rays. We notably remark that while our simulation is characterized by a significant adiabatic contraction of the DM density in the central parts of the galaxy, the background is still strong enough to induce a rather modest ratio. This result is rather unexpected, since adiabatic contraction is usually thought of as a very optimistic case for DM signal predictions. One could still take a lighter WIMP to get a larger flux. Nevertheless, there is another physical reason: adiabatic contraction stems from the over-cooling of baryons, which also implies a large central gas density, and a high local star formation rate (and thereby a large local SN explosion rate and CR density). Therefore, adiabatic contraction amplifies both the DM signal and the background. Since gravitation affects DM and baryons the same, one could argue that the signal should still be favored because it is proportional to the squared DM density. Nevertheless, the background is somehow also proportional to the squared baryon density. Indeed, locally, the CR density is proportional to the number density of sources, which is itself proportional to the gas density (the star formation rate scales linearly with the gas density in our simulation). Therefore, since the background flux is set by the product of the gas and CR densities, this corresponds to squaring the overall baryon density (CRs are actually much more diluted than the gas because of diffusion, which slightly alters the argument, though keeping it qualitatively valid).

We have incorporated sophisticated ingredients of CR physics in a cosmological simulation including baryons. We focused on a zoomed-in galaxy with properties reasonably comparable to those of the MW. We have calculated the CR density self-consistently after having accurately localized their sources (SN-like events) in space and time, and convoluted it with the interstellar gas density to calculate the DGRE. We have determined the DGRE that a virtual Earth-like observer located in the disk would detect, and discussed separately the amplitude of the DM annihilation signal and that of the astrophysical background. We have shown that even in an adiabatically contracted halo (not necessarily to be compared with the MW), the signal-to-noise ratio is not necessarily large. This is due to the fact that both the DM and baryon densities are correlated in such a case, which induces an amplification in both the signal and background. Irrespective of any putative similarities or differences with the MW, a firm conclusion is that from this unprecedented top-bottom approach, we

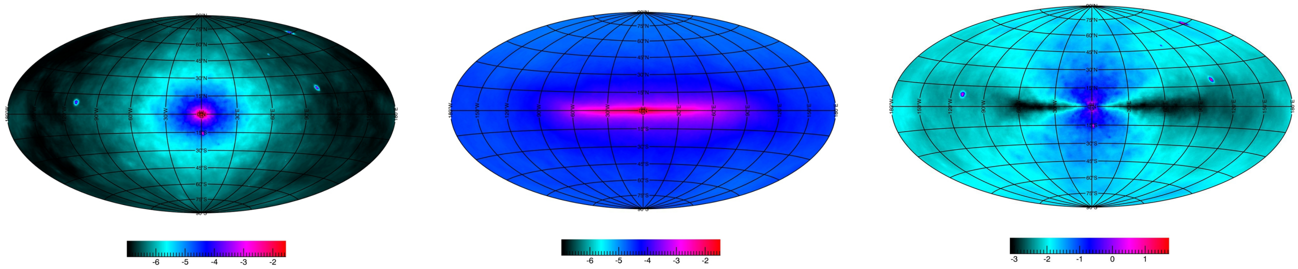

FIG. 3. Left: log-scaled skymap of the DM annihilation gamma-ray signal ($\log_{10}\{\Phi(>1\,\mathrm{GeV})/\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\}$), assuming 100 GeV WIMPs annihilating into $b\bar{b}$ quark pairs. Middle: DGRE due to CR interactions with the interstellar gas (same units as in left panel). Right: Signal-to-background ratio (log scale).

demonstrate that indirect DM detection is in any case challenging, whatever the central DM shape. The best targets remain the DM subhalos, some of which are found to be observable in our simulated galaxy, though with values of M/d^2 much more favorable than those of the known MW satellites. The central parts of the galaxy are very interesting zones to which we will further dedicate a detailed analysis. This approach can be generalized to all cosmic tracers of DM annihilation, like antimatter CRs, radio and X emissions, and neutrinos. Even more globally, it may serve as a powerful diagnostic tool to test galaxy formation itself from its high-energy properties.

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